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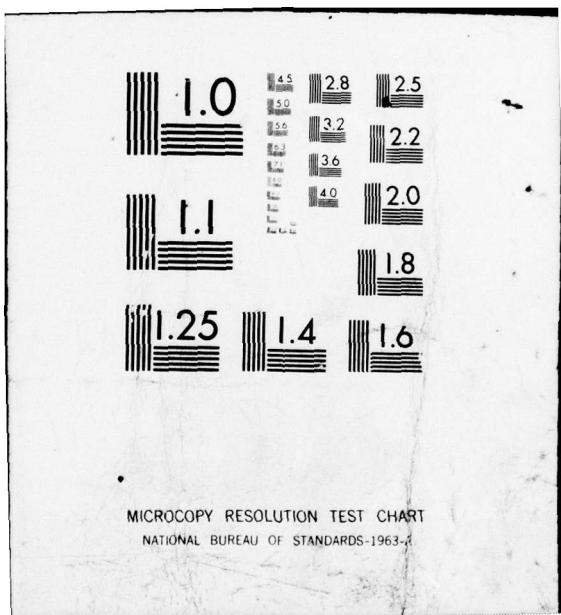
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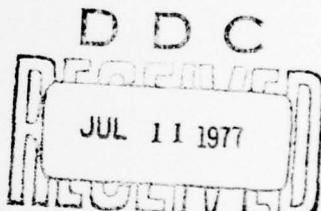
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## TEMPERATURE REGIME OF WATER IN THE NEAR SHORE ZONE OF THE RESERVOIR OF THE VILYUYSK HYDROELECTRIC POWER STATION

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I.P. Konstantinov

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Temperature Regime of Water in the Near-Shore Zone  
of the Reservoir of the Vilyuysk Hydroelectric Power Station

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The thermal effect of water on frozen soil is one of the important factors involved in the reformation of the shores of artificially constructed reservoirs in areas where permafrost soil occurs. Therefore, one aspect of the program of observations associated with the formation of the shores of the Vilyuysk Reservoir, carried out by the Vilyuysk Permafrost Scientific Research Station of the Institute of Mathematics, Siberian Branch, USSR Academy of Sciences, was the monitoring of water temperature.

The observations were carried out 25 km above the section line of the dam in the vicinity of the Duranin broad, where

the water is between 4 and 5 m deep. The water temperature was measured with a chain of type MMT-4 thermistors, mounted on a float. The sensors were set at depths of 10, 50, 100, 200, 300, 400, and 500 cm.\* The distance from the water's edge to the temperature sensors was 10 to 12 m on the average. The intervals between measurements were 3 hours long.

The stationary measurements were supplemented by periodic temperature measurements in the central part of the reservoir, where the water reaches its maximum depth of 48 to 50 m. In addition, occasional synchronous water temperature measurements were carried out in various parts of the reservoir.

The observations began during the first decade of May, in other words at the end of the hydrologic winter, when the water in the reservoir and the bedrock layer have the lowest temperature reserve. The bottom temperature during this period was 1.2 to 1.5° at a depth of 2 to 8m and 2.6 to 3.2° where the water was 30 to 50m deep; the average water temperature measured vertically was 1 to 1.4° and 2.1 to 2.5°, respectively. This relatively high value for the water temperature at the end of the winter, was due to the considerable temperature reserves in the reservoir and its low flow rate (the data from our measurements made from the ice indicate that runoff does not exceed 3 to 3.5 cm/day).

The heating of the water beneath the ice in spring begins to be felt at the beginning of the second half of May, since it is only at this time that the snow and snow-covered ice on the surface of the ice cover begin to melt. The intensity of the heating of the water beneath the ice during the second half of May can be estimated from the data in Table 1, which shows the water temperature during the period of melting of the ice in the shore area of the reservoir during May of 1974.

It is interesting to note that during the second half of May the thickness of the ice decreased from 107 to 76 cm.

At the beginning of June, the temperature sensors were shifted to the open water area (at the edge), where the thermal regime is distinctive and is characterized not only by a higher temperature owing to the heating of the water as a result of the lack of an insulating layer of ice, but also by an unstable temperature stratification. The daily variations in solar radiation penetrating the water cause corresponding

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\* The temperature sensors were adjusted as the depth of the water changed.

Table 1

Глубина подо- ледник. м	Температура воды по числам								Прираще- ние темпе- ратуры м
	14	17	19	21	23	25	27	29	
0.5	0.96	1.07	1.25	1.53	1.61	1.72	1.84	2.10	1.14
1.0	0.95	0.99	1.31	1.48	1.59	1.70	1.76	1.90	0.95
1.5	0.92	1.00	1.10	1.44	1.57	1.62	1.74	1.80	0.88
2.5	0.96	1.04	1.31	1.51	1.62	1.72	1.86	1.90	1.94
3.5	0.95	1.10	1.28	1.50	1.62	1.72	1.84	1.90	0.84
d 4.5	1.00	1.23	1.45	1.54	1.63	1.73	1.82	1.90	0.90
8.6	1.39	1.41	1.53	1.64	1.67	1.66	1.81	1.90	0.51
Средняя значение чисел	1.04	1.16	1.34	1.50	1.57	1.65	1.78	1.85	1.86

- a) Depth of water beneath the ice, m
- b) Water temperature in degrees
- c) Temperature increase, m
- d) Average

changes in water temperature. At various times, the water surface temperature reaches 5.1 to 5.3°, and the temperature at the bottom is 4.3 to 4.6° (for water depths up to 1 m). The drifting of the ice, initially within the limits of the shoreline, and later throughout the water area, reduces the water temperature at its surface to 1.2°, and down to 1.0 to 2.1° at the bottom (depending on the depth).

Complete disappearance of ice from the Vilyuysk Reservoir and the final passage of the temperature through 4° takes place between the 15th and 17th of June.

During the period of intensive thawing of the ice and the opening up of the reservoir (15 May to 15 June) the change in the heat content of a column of water with an area of 1 m<sup>2</sup> and a depth of 4.5 m requires an amount of heat which is equal to

$$Q_1 = 1 \cdot 1000 \cdot 3-4.5 = 13,500 \text{ kcal/m}^2 = 1.3 \text{ kcal/cm}^2.$$

To melt ice 1.07 m thick, an amount of heat is required equal to

$$Q_2 = 920 \cdot 1.07 \cdot 80 = 79,000 \text{ kcal/m}^2 = 7.9 \text{ kcal/cm}^2.$$

Hence, during the warming period of spring and summer, the amount of heat required to thaw the ice and heat the water (including that beneath the ice) is 9.2 kcal/cm<sup>2</sup>, produced as

a result of absorption of solar radiation by the water and the input of heat from the atmosphere.

This is followed by the period of summer heating of the water, which lasts until the second decade of August. During this period, the transfer of heat within the mass of water is accomplished primarily as a result of turbulent mixing. The only exception is on several days at the beginning of the second half of June, when temperature equalization occurs during the nocturnal temperature drop with a dead calm, and changes occur with depth as a result of free convection.

As a result of regular observations of the water temperature (1971-1974) it became clear that the summer period is characterized by considerable variations in water temperature. The maximum daily amplitude of temperature variation at the surface is 6.2 to 14.1° (July), 3 to 8.5° (August), while at the bottom the corresponding temperatures are 4.2 to 8.7° (July) and 2.9 to 8° (August). The maximum temperature of the water at the surface reaches 22 to 26.5° (July), 21 to 24.7° (August), and at the bottom the values are 14.6 to 19.8° (July) and 15.3 to 19.7° (August). The time at which the maximum temperature value is reached at the Vilyuysk Reservoir varies between 1500 and 2100 hours and is often observed at 1600 to 1800 hours. The time at which the minimum temperature occurs is more stable and in most cases is between 0600 and 0900 hours. The water temperature in the deep layers (30 to 40 m) changes by 0.2 to 0.3° in the course of a day.

The types of vertical distribution of water temperature are shown in Figure 1. The initial stage of the heating process is characterized by a linear decrease in temperature in the 0.5 to 1 m layer (Fig. 1a). Later, the upper heated layer is separated from the lower layer by a layer of temperature discontinuity (Fig. 1b), whose lower limit gradually moves downward. When the waves are small, there is a characteristic linear distribution of temperature with a maximum gradient in the upper 3-meter layer (Fig. 1c, d). When the waves are high, although this is rare at this time, the temperature discontinuity layer is disrupted. However, when the wave action dies down, thermal stratification occurs, and the situation returns nearly to what it was in the beginning. This is due to the fact that during the period of summer heating of the water the action of the mixing produced by the wind does not consist in a loss of heat from the water but in its redistribution.

The third period, that of autumn cooling (down to 4°), lasts from the second decade of August to the end of October. During this time the air temperature is almost always lower than the water temperature. Under conditions of increasing

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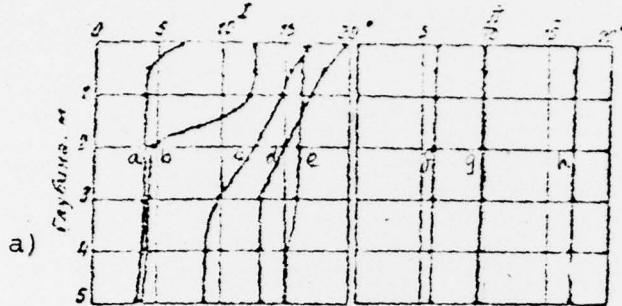


Fig. 1. Curves showing vertical distribution of temperature of the water in the zone near the shore:

1 - period of summer heating; (I) - period of autumn cooling; a - 16 June; b - 18 June; c - 29 June; d - 2 July; e - 16 July; f - 11 August; g - 22 September; h - 13 October

Key: a) depth, m

mixing caused by the wind, which takes place in September and October, there is an intensification of heat exchange between the water and the atmosphere and the bedrock, as well as a redistribution of heat throughout the depth of the water. Nevertheless, the water temperature in the reservoir decreases quite slowly as a result of a large amount of heat which has accumulated over the summer. For example, from the second decade of August to the second decade of October, the average water temperature decreases by  $9.5^{\circ}$ . During this time, the surface layers of water cool by  $9.9^{\circ}$ , while those near the bottom cool  $8.9^{\circ}$ . Table 2 shows the average decade and average monthly temperature of the water in the zone near the shore in the Vilyuysk Reservoir for the period 1972-1974 (in degrees).

The water temperature passes through  $4^{\circ}$  at the end of September, first of all in the upper reaches of the reservoir and in the shallow areas of its numerous inlets. In the middle and lower parts of the reservoir, the temperature passes through  $4^{\circ}$  during the third decade of October.

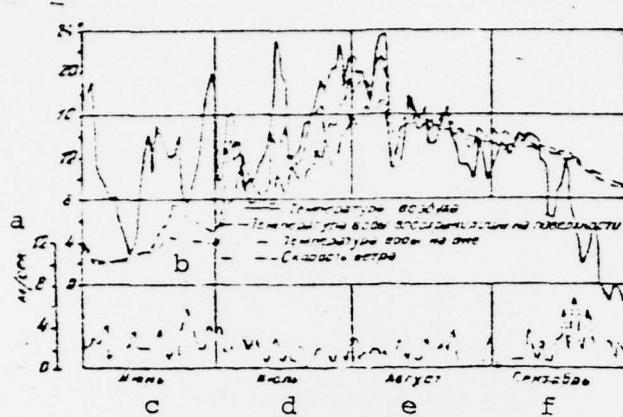


Fig. 2. Change in average daily temperature of the air, at the surface of the water, and at the bottom (1974).

a - meters/sec; b - air temperature, water temperature at the surface of the reservoir, temperature of the water at the bottom, wind speed; c - June; d - July; e - August; f - September.

Table 2

Глу- бина, м	Июнь b				Июль c				Август d				Сентябрь e				Октябрь f			
	I	II	III	Cр.	I	II	III	Cр.	I	II	III	Cр.	I	II	III	Cр.	I	II	III	Cр.
0	2.3	5.1	8.9	5.4	12.1	15.3	17.4	14.9	18.1	15.1	15.0	16.1	13.7	11.5	9.4	11.5	7.1	5.2	3.6	5.3
0.5	2.3	4.7	7.9	5.0	11.4	14.1	16.8	14.1	17.5	14.9	14.6	15.7	13.6	11.5	9.4	11.5	7.1	5.2	3.6	5.3
1.0	2.3	4.6	7.2	4.7	11.1	13.5	16.3	15.7	17.2	14.8	14.4	15.5	13.5	11.6	9.4	11.5	7.0	5.1	3.6	5.3
2.0	2.3	4.4	6.9	4.5	10.4	12.5	15.2	12.7	16.7	14.6	14.2	15.2	13.4	11.5	9.4	11.4	7.0	5.1	3.6	5.3
3.0	2.4	4.3	6.5	4.4	10.2	11.9	14.3	12.1	16.1	14.4	14.0	14.8	13.2	11.5	9.4	11.4	7.0	5.1	3.6	5.3
4.0	2.5	4.5	6.1	4.4	9.6	11.2	13.5	11.4	15.1	14.3	13.7	14.4	13.2	11.4	9.4	11.3	7.0	5.1	3.6	5.3
5.0	2.5	4.3	5.9	4.2	9.2	10.8	12.7	10.9	15.8	14.0	13.0	13.6	13.0	11.6	9.3	11.0	7.0	5.1	3.6	5.3
Cр.	2.4	4.6	7.1	4.7	10.6	12.8	15.2	12.8	16.4	14.8	14.1	15.0	13.4	11.5	9.4	11.4	7.0	5.1	3.6	5.3

a - Depth, m; b - June; c - July; d - August; e - September;  
f - October

The pattern of changes in water temperature at the surface and at the bottom for the period June-September 1974 is shown in Fig. 2. As we can see from the values listed there, the change in water temperature, especially during the summer period, is accompanied by sharp variations. Prior to the first decade of August, the water temperature is less than the air temperature, but beginning in the second decade of August and lasting until freezing, on the other hand, the water temperature is above the air temperature.

The measurement of water temperature just before freezing occurs shows that only the surface layers are subjected to supercooling, while those near the bottom (depending on the depth) retain a temperature from 2.8 - 3° to 3.5 - 3.7°. The only exception consists of those areas where the backwaters of the dam taper off, and the process of freezing resembles that which takes place in rivers.

In the middle and lower parts of the reservoir, the inlets freeze first, after which shore ice forms along the main channel, gradually expanding into an ice cover. Finally the middle of the reservoir freezes. The average date for ice formation at the lower end of the reservoir is 2 to 4 November. Hence, the length of the ice-free period in the reservoir is 140 to 142 days.

As mentioned earlier, at the end of winter, at a water depth of 2 to 8 m, the minimum temperature at the bottom was 1.2 to 1.5° and 2.6 to 3.2° at a depth of 30 to 50 m. If we take into account that the corresponding bottom temperature prior to freezing at these depths is 2.8 to 3° and 3.5 to 3.7°, we can see that during the long winter the temperature in the riparian zone drops at the rate of 0.25 to 0.27° per month and at the rate of 0.10 to 0.12° per month in the deep-water area.

Hence, the average annual temperature of the surface of the water and of the bottom in the near-shore zone of the Vilyuyesk Reservoir is distributed as follows (Table 3):

Table 3

a	Горизон-	I-V	VI	VII	VIII	IX	X	XI-XII	$\Sigma$	c
b	Поверхность	0	5.4	14.9	16.1	11.5	5.3	0	4.4	
	Дно (5 м)	2.5-1.3	4.2	10.9	13.6	11.0	5.3	2.0-2.6	5.0	

a - horizons; b - surface, bottom (5 m); c - year.

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The average (annual) water temperature, measured as a cross section and as a function of width, is  $4.6^{\circ}$  in the part of the Vilyuysk Reservoir which is near the dam [2]. It is interesting to note that the mean annual water temperature in the deep part of the Bratsk Reservoir in 1964, 1965 and 1966 was  $3.76^{\circ}$ ,  $3.84^{\circ}$  and  $3.63^{\circ}$ , respectively [1]. Hence, despite the harsher climatic conditions (mean annual air temperature at the Chernyshevskiy urban-type settlement  $-8.3^{\circ}$ , and  $-2.6^{\circ}$  in the city of Bratsk) and the presence of permafrost soil in the bed of the reservoir, the water temperature in the Vilyuysk Reservoir is higher than the water temperature in the Bratsk Reservoir.

Table 4 lists data which characterize the change in the heat content of the water in the near-shore zone of the Vilyuysk Reservoir for the period 1972-1974. It is evident that the maximum amount of heat contained in the mass of water is observed during the second decade of August. Most of the heat is consumed to increase the heat content of the water during the first month after the ice thaws.

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Table 4

a Месяц	b Декада	Температура и теплоемкость воды, ккал/см <sup>2</sup>			c Среднее	d Среднее
		1972	1973	1974		
Июнь	I	1200	1150	1090	112	
	II	2200	1950	1840	194	
	III	2400	2750	1810	240	
	Среднее j	2360	1930	1560	185	
Июль	I	4600	3900	3430	3970	
	II	4450	4050	3880	4230	
	III	6250	5350	5740	574	
	Среднее j	5100	4530	4360	4690	
Август	I	6750	5950	5480	6420	
	II	7350	6650	6100	6570	
	III	5250	6800	5640	593	
	Среднее j	6450	6370	6040	6240	
Сентябрь	I	5250	7200	5240	590	
	II	4650	6650	4920	541	
	III	4100	5200	4080	443	
	Среднее j	4600	6350	4750	5240	
Октябрь	I	3000	3450	3160	3290	
	II	2400	2450	2320	2390	
	III	1600	1850	1400	1630	
	Среднее j	2300	2550	2290	2390	

a - month; b - decade; c - heat content of water mass, kcal/cm<sup>2</sup>; d - average; e - June; f - July; g - August; h - September; i - October; j - average.

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